AD-A143 298 MODIFIED THOMSON PARABOLA ION SPECTROMETERS FOR USE IN LASER GENERATED PLASMA EXPERIMENTS(U) NAVAL RESEARCH LAB WASHINGTON DC S T KACENJAR ET AL. 29 JUN 84 1/1

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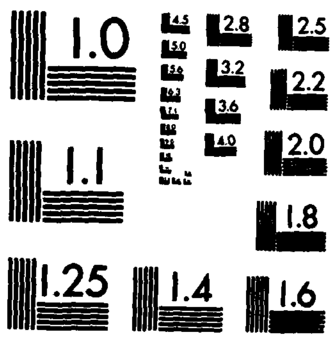

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NRL Memorandum Report 5363

Modified Thomson Parabola Ion Spectrometers for Use in Laser Generated Plasma Experiments

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June 29, 1984

This research was sponsored by the Defense Nuclear Agency under Subtask 125BMX10, work unit 00024 and work unit title "Early Time Plasma".

NAVAL RESEARCH LABORATORY
Washington, D.C.

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 5363	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Research Laboratory 6b. OFFICE SYMBOL (If applicable) Code 4732	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State and ZIP Code) Washington, DC 20375	7b. ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Defense Nuclear Agency 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State and ZIP Code) Washington, DC 20305	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO.: 62715H PROJECT NO.: TASK NO.: WORK UNIT NO.: DN280-234
11. TITLE (Include Security Classification) (See page ii)	

12. PERSONAL AUTHOR(S)
Kacenjar, S.T. and Manka, C.K.*

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Interim	FROM TO	June 29, 1984	37

16. SUPPLEMENTARY NOTATION
*Sam Houston State University, Huntsville, TX 77340 (Continues)

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Ion spectrometer; Thomson Parabola; Laser produced plasmas; Charged particle energy analyzer

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Two devices for the measurement of the velocity distribution of ions from laser-produced plasmas are presented. Characteristics of the normal Thomson Parabola apparatus are examined under the constraints of small overall dimensions (few centimeters) and moderate ion velocities (1 × 10^7 cm/s - mid 10^8 cm/s). A second device uses a novel modification of the Thomson Parabola apparatus to produce separation of the ionic species into linear traces. The same constraints are employed for this apparatus. The use of solid state track detectors, charge collectors, and microchannel plates in both devices are discussed.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED X SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL S. T. Kacenjar	22b. TELEPHONE NUMBER (Include Area Code) (202) 767-5279 22c. OFFICE SYMBOL Code 4730

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE

11. TITLE (Include Security Classification)

Modified Thomson Parabola Ion Spectrometers for Use in Laser Generated Plasma Experiments

16. SUPPLEMENTARY NOTATION (Continued)

This research was sponsored by the Defense Nuclear Agency under Subtask I25BMXIO, work unit 00024 and work unit title "Early Time Plasma."

CONTENTS

A-1

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Introduction

The study of the velocity distribution of the various positive ion species generated in laser-produced plasmas can reveal important information of various plasma processes occurring during the initial production and subsequent expansion of the plasma. Several schemes[1,2,3,4] have been used to measure these distributions; however, complications in the analysis often result if electronic detection systems are implemented. One reason for this is that the minimum ion flux required for electronic detection becomes unacceptably large for low velocity ions. This follows because space charge effects dominate the process of beam expansion at low velocities which in turn necessitates the use of large collecting detectors and thus reduces velocity resolution. Another complication arises when the ion strikes an electronic detector and generates secondary electrons which may be erroneously interpreted as additional ion flux. Since the number of secondaries is velocity dependent significant distortion in the measured ion distribution may result if velocities vary considerably over the measurement. For these reasons it is clear that non-electronic detection can provide important advantages to circumvent these aforementioned difficulties.

This review presents two such systems which have the flexibility to use either charge collectors, solid state track detectors, or microchannel plates. A discussion on the advantages and limitations of each will be presented. Emphasis is placed on designs for measuring the absolute flux of ions with velocities from 10^7 to the mid 10^8 cm/s.

The Thomson Parabola

Much work has been done using the Thomson Parabola in laser-fusion experiments.[5,6] Schematically, the basic configuration is shown in Figure 1. Ions enter the spectrometer through a pinhole and are then deflected by an external electric, E, and magnetic, B, field. These ions enter the spectrometer initially transverse to the applied fields. After a finite distance, they are deflected and the degree of bending is a function of the field parameters as

Manuscript approved April 24, 1984.

well as the ion's charge-to-mass ratio and velocity (V). Detailed analysis of the deflection shall not be derived here since such calculations have been performed by numerous authors.[7,8,9] The results of these analyses show that the overall x and y displacements are given by

$$x = \left(\frac{Z}{A}\right) \frac{eB}{m_p V} \ell \left(L + \frac{\ell}{2}\right) \tag{1}$$

$$y = \left(\frac{Z}{A}\right) \frac{eE}{m_p V^2} \ell \left(L + \frac{\ell}{2}\right) \tag{2}$$

where m_p is the proton mass and the remaining variables are defined in Figure 1. Combining Equations (1) and (2) to eliminate V gives

$$y = \left(\frac{E}{B}\right) \left(\frac{A}{Z}\right) \left(\frac{m_p}{e\ell\left(L + \frac{\ell}{2}\right)}\right) x^2 \tag{3}$$

Therefore, ions of a given charge-to-mass ratio fall on regions forming parabolas. If one divides Equation (1) into Equation (2) then

$$y = \left(\frac{E}{B}\right) \frac{1}{V} x \tag{4}$$

which indicates that straight lines emanating from the origin on the xy coordinate plane are lines of constant velocity (see Figure 2).

On the other hand, for extended velocity ion distributions it can be seen that for a given x coordinate, X_o, the ability to separate individual traces is a function of $\frac{A}{Z(Z+1)}$ namely

$$\Delta y = y\left(\frac{A}{Z}\right) - y\,\frac{A}{Z+1} \tag{5}$$

$$= \frac{E}{B} \frac{m_p X_o^2}{e\ell(L + \ell/2)} \frac{A}{Z(Z+1)} \tag{6}$$

This effect is illustrated in Figure 2. By knowing this dispersion, one can then identify various charge states even if not all charge states are present. It is interesting to note that for a given type of ion (i.e., carbon ions), the distance between points of constant velocity on adjacent parabolas does not change in spacing, namely,

$$\Delta R \equiv (x^2_{z+1} + y^2_{z+1})^{1/2} - (x_z^2 + y_z^2)^{1/2} \tag{7a}$$

$$\Delta R = \frac{1}{A} \frac{e\ell}{m_p V} (L + \frac{\ell}{2}) \left[B^2 + \frac{E^2}{V^2}\right]^{1/2} \tag{7b}$$

Therefore, if the ions produced all have nearly the same velocity, then identification can become difficult. If ΔR is obtained experimentally the last expression can also be solved for the ion velocity giving

$$v = \frac{\beta B}{\sqrt{2}} \left[1 + \left(1 + \frac{4E^2}{\beta^2 B^4}\right)^{1/2}\right]^{1/2} \tag{8}$$

where

$$\beta \equiv \frac{e\ell(L + \frac{\ell}{2})}{Am_p \Delta R} \tag{9}$$

Two factors limit the practical dynamic range of the Thomson Parabola. First, space charge will tend to expand the low energy portion of the parabolas making measurements difficult. Second, the lower pole magnet will stop the low velocity ions from leaving the pole piece region. To calculate this lower limit velocity, the pinhole to lower pole distance, H, must be specified. Then the minimum velocity, V_{min}, is given by,

$$V_{min} = \ell \left[\frac{1}{2} \left(\frac{Z}{A}\right) \frac{eE}{m_p H}\right]^{1/2} \tag{10}$$

and is plotted in Figure 3 for various charge-to-mass states. However, one cannot make H abritrarily large to increase the dynamic range. A system constraint that ℓ/H be greater than ~ 4 is necessary to avoid serious fringe field effects. In addition, ℓ cannot be made arbitrarily large because of beam expansion due to space charge. In particular, beam divergence is given by[9]

$$r_1 = \frac{r_o(L + \ell)\ eZ\sqrt{n}}{\sqrt{2}\ (\varepsilon_o \mathcal{E})^{1/2}} \tag{11}$$

where: r_o = initial pinhole radius (cm)

r_1 = radial divergence at the image plane (cm)

$\mathcal{E}$ = ion energy (eV)

e = electronic charge (e.s.u.)

$\varepsilon_o = 8.85 \times 10^{-12}$

n = ion number density (#/cm^3)

Equation (11) can be expressed in terms of velocity and is given as

$$r_1 = 158.2\ \frac{r_o(L + \ell)Z\sqrt{n}}{\sqrt{A}\ \ V} \tag{12}$$

where all terms are in terms of practical c.g.s. units. If one combines Equation (10) and (12), then the maximum beam expansion can be determined, namely,

$$r_{max} = 2.3 \times 10^{-3}\ r_o\ (1 + \frac{L}{\ell})\ \sqrt{Zn\ \frac{H}{E}} \tag{13}$$

where all terms are in c.g.s. units except for the electric field given in units of volts/m. Notice that r_{max} is independent of ion mass. This is because the minimum velocity which can pass through the spectrometer is inversely proportional to the square root of the ion mass. This exactly cancels with the reduction in beam divergences because of ion inertia. Figure 4 shows the calculated dependence of $r_1/\ r_0$ as a function of $\frac{\sqrt{A}}{Z}$ V for various ion densities.

Another factor which influences the final beam expansion is due to geometrical divergence. Even for a point source, the beam expansion at the image plane is given by

$$\tilde{r}_2 = \frac{r_o}{D}\ (D + \ell + L)\ - r_o \tag{14a}$$

$$= \frac{r_o}{D}\ (\ell + L) \tag{14b}$$

where D is the target-pinhole distance. Typical beam expansion of 10% can occur when D is taken to be 50 cm and L and ℓ are taken to be 2.5 cm. This effect can be comparable or greater than the beam expansion due to space charge at high ion velocities.

Besides determining the minimum ion velocity required to traverse the spectrometer, the pinhole-to-pole-gap distance will also determine a maximum y displacement which is independent of charge state. This is given by

$$y_{max} = H\left(1 + \frac{2L}{\ell}\right) \tag{15}$$

and is plotted for various H values in Figure 5.

A conventional Thomson Parabola type system under consideration will analyze ions with velocities from 10^7 to 10^8 cm/s. For entrance pinhole diameters of less than 50 μm, space charge or geometric divergence does not appear to be a serious problem. The lower charge state should be more easily resolved because of smaller beam divergence and wider separation between adjacent parabolas as indicated in Equations (11) and (6) respectively.

One method for detection of ions utilizes solid state track detectors which has been successfully employed when ion velocities are in excess of a few times 10^8 cm/s.[10] An important proviso to this, however, is that the ion strikes the surface normally. If the ion strikes the surface at an angle, the threshold velocity will be increased. To date, the most sensitive track detector used for ion registration is CR-39.[11] It can be chemically etched in NaOH (6.25 N) from 2 to 3 hours at 70^{o} C and then examined optically under a microscope. The efficiency of detection is close to 100% when velocity threshold conditions are reached and is insensitive to electron or x-ray backgrounds.

Such a detector is currently being examined to record the ion parabolas. To detect the upper ends of the parabolas where the ion velocities are small (i.e., less than 2×10^8 cm/s), it will be necessary to include a post-acceleration stage to accelerate the ions to velocities necessary for track registration. A spectrometer which incorporates a post-acceleration stage is shown in Figure 6. Experimental studies suggest that an acceleration potential of at least 18 KV is necessary for satisfactory track registration.[10]

With the introduction of the acceleration potential, the track trajectories are no longer parabolas. After the ion leaves the deflection plates it travels a distance L in rectilinear motion (i.e., no forces applied on the ion). The ion velocity components in the x and y directions are given by

$$\dot{x} = \frac{zeB\ell}{Am_p} \tag{16a}$$

$$\dot{y} = \frac{zeE\ell}{Am_p V} \tag{16b}$$

When the ion reaches the acceleration grid, it then travels a distance $\tilde{L}$ from the grid to the detector's surface. The time τ, required to travel this distance is given by

$$\tau = \left[-V + \left(V^2 + 2\left(\frac{ze}{Am_p}\tilde{E}\right)\right)^{1/2} \right] / \left(\frac{ze}{Am_p}\tilde{E}\right) \tag{17}$$

where $\tilde{E}$ is the electric field in the acceleration region. Therefore, the ion travels an additional distance $\dot{x}\tau$ and $\dot{y}\tau$ in the x and y directions respectively. This results in the generation of ion traces governed by the equations

$$x = \left(\frac{Z}{A}\right) \frac{eB}{m_p V} \ell \left(L + \frac{\ell}{2} + V\tau\right) \tag{18a}$$

$$y = \left(\frac{Z}{A}\right) \frac{eE}{M_p V^2} \ell \left(L + \frac{\ell}{2} + V\tau\right) \tag{18b}$$

Using Equations (17) and (18a) one can find an expression for V given by

$$A_3 V^3 + A_2 V^2 + A_1 V + A_0 = 0 \tag{19}$$

where

$$A_0 = \left[\frac{Ze\tilde{E}}{Am_p} \left(L + \frac{\ell}{2}\right)\right]^2 \tag{20a}$$

$$A_1 = -2\left(\frac{Z}{A}\right) \frac{e\tilde{E}}{m_p \ell \beta}\left(L + \frac{\ell}{2}\right) x \tag{20b}$$

$$A_2 = \left(\frac{\tilde{E}X}{B\ell}\right)^2 - 2\left(\frac{Z}{A}\right) \frac{e\tilde{E}}{m_p}\left(L + \frac{\ell}{2} + \tilde{L}\right) \tag{20c}$$

$$A_3 = 2\frac{\tilde{E}x}{B\ell} \tag{20d}$$

It is now possible to solve for V and substitute it into equation (18b) to find the analytic relation between x and y.

It is not surprising however that for certain range of parameters the ion traces should appear to be approximately parabolic. Consider the two extreme limits when $\tilde{E} \to \infty$ and $\tilde{E} \to 0$. For $\tilde{E} \to \infty$, the ions trav across the acceleration region in a time approaching zero. This implies at the spatial distribution does not change while passing through the gap Thus the ion distributions appear to be parabolic. In the other extreme ca. n $\tilde{E} \to o$, the ions free stream and the analysis is equivalent to the typical Thomson Parabola. Therefore, again the ions should form parabolic traces. Figure 7 shows the transition from almost no accelerating field to very large fields. As demonstrated, the parabolas expand outward as the field is reduced.

One feature which does remain exactly the same is that straight lines emanating from the origin on the xy coordinate plane are lines of constant velocity. This is shown by dividing Equation (18a) into (18b) into each other and again producing Equation (4).

Even though detection can be achieved with the addition of an acceleration potential, it is by no means a trivial matter to record low charge state ions. For example, C^{+1} initially having a velocity of 2 x 10^7 cm/s would require an acceleration potential of ~ 240 KV before reaching a velocity necessary for registration. Such requirements are severe and may not be easily achievable.

To circumvent this difficulty, microchannel plates (MCP) may be required. Here gains from 10^4 to 10^8 are possible depending on whether a single or multistage MCP is used. However, such devices must be operated in vacuum having pressures of 10^{-6} torr or better. If the vacuum system in which the plasma is generated does not meet this requirement, differential pumping must be utilized

inside the spectrometer. A recent development by Galileo Electro-Optics Corporation now offers curved-channel microchannel plates (C^2MCP)[12,13] with gains as high as 10^6 with 15-30 μm spatial resolution. These devices have significantly reduced the degree of ion feedback which increases the operating lifetimes compared with conventional multi-stage microchannel plates (i.e., chevron configuration). In addition, the C^2MCP's do not suffer from the space charge defocusing problems inherent in the chevron devices.

A third method for the detection of ions is the use of charge collectors which are shaped in the appropriate forms. This technology has been used successfully in the past to obtain semi-quantitative information of the ion distribution. However important limitations to such an approach not only includes the problem of secondary electron emission but also the inflexibility of the devices. Specific parabolas must be constructed for each charge state. If other type ions are present, a new set of collector strips need to be made and accurately positioned. In addition, factors such as fringe field effects of the deflector plates can introduce focusing aberrrations which are not accurately known making exact fabricating and positioning of the collectors even more difficult. Lastly, appropriate shielding is required to eliminate the large RF background level occurring during the time of ion collection.

Modified Thomson Parabola

A variation of the standard Thomson Parabola is shown in Figure 8. Again the electric and magnetic fields are initially perpendicular to the ion trajectory. However unlike the standard Thomson parapola, the modified Thomson Parabola positions the detector inside the magnets' gap perpendicular to the applied fields. Such a device has not been reviewed in the literature and thus an analysis of the focusing properties of the spectrometer will be presented.

The equation of motion for an ion of charge z and a mass Am_p is given by

$$Am_p\ddot{x} = -\dot{Z}ezB \tag{21a}$$

$$Am_p\ddot{y} = ZeE \tag{21b}$$

$$Am_p\ddot{z} = Ze\dot{x}B \tag{21c}$$

Taking the time derivation of Equation (21c), solving for $\ddot{x}$, and substituting into Equation (21a) yields

$$\ddot{V}_z = -\left(\frac{ZeB}{Am_p}\right)^2 V_z \tag{22}$$

which has the general solution,

$$V_z = C_1\cos(\omega t) + C_2\sin(\omega t) \tag{23}$$

where $\omega = (\frac{Ze}{Am_p}B)$ (ion cyclotron frequency) (24)

The initial conditions that $V_z = V_o\cos\,\theta$ and $\dot{V}_z = \frac{Ze}{Am_p}\,BV_o\,\sin\theta\cos\phi$ at t=0 requires that

$$C_1 = V_o\cos\theta \tag{25a}$$

$$C_2 = V_o\sin\theta\cos\phi \tag{25b}$$

where θ and ϕ are the usual spherical coordinate angles and are defined in Fig. 9. Upon integration of Equation (23) and applying the boundary condition that z=0 at t=0 gives

$$z = \frac{V_o}{\omega}\,[\cos\theta\sin(\omega t) - \sin\theta\cos\phi(\cos(\omega t)-1)] \tag{26}$$

Using Equations (21a) and (23) and the initial condition $V_x = V_o\sin\theta\cos\phi$ at t=0, one can calculate V_x namely,

$$V_x = V_o\cos\theta\cos(\omega t) + V_o\sin\theta\cos\phi\sin(\omega t) \tag{27}$$

Integrating Equation (27) and applying the boundary condition that x=0 at t=0 gives

$$X = \frac{V_o}{\omega}\,[\sin\theta\cos\phi\sin(\omega t) + \cos\theta(\cos(\omega t)-1)] \tag{28}$$

combining Equations (26) and (28) results in

$$x/z = \frac{\tan\theta\cos\phi - \tan(\omega t/2)}{1-\tan\theta\cos\phi\tan(\omega t/2)} \tag{29}$$

Since ω is a function of Z/A, then for a given charge-to-mass ratio, the slope of the trace on the x-z plane is a function of the entrance angle and the time spent inside the spectrometer. This time can be easily determined by integrating Equation 21b and the boundary conditions $V_y = V_o \sin\theta\sin\phi$ and $y = \tilde{H}$ at t=0 then this equation integrates to obtain

$$t = \left[V_o \sin\theta\sin\phi + \left(V_o^2 \sin^2\theta\sin^2\phi + 2\frac{Ze}{Am_p} E\,(y-\tilde{H})\right)^{1/2}\right] \Big/ \frac{Ze}{Am_p} E \tag{30}$$

For a given x-z plane, the time spent inside the spectrometer is a function of Z/A as well as θ and ϕ. By collimating the ion beam, so that to lowest order θ and ϕ are set equal to zero, the above equations simplify to

$$z = \frac{V_o}{\omega} \sin\omega t \tag{31}$$

$$x = \frac{V_o}{\omega} (\cos\omega t - 1) \tag{32}$$

$$x/z = -\tan\,(\omega t/2) \tag{33}$$

$$t = \left[2\,\left(\frac{Am_p}{Ze}\right)\left(\frac{y-\tilde{H}}{E}\right)\right]^{1/2} \tag{34}$$

$$\omega t = B\left[\frac{2(y-\tilde{H})}{E}\left(\frac{Ze}{Am_p}\right)\right]^{1/2} \tag{35}$$

Notice that both x and z are directly proportional to V_o. If one plots z vs. (-x) one would obtain a family of straight lines all of which would intersect the origin. The slope of each line would be determined by the charge-to-mass ratio of the ion. This is a considerable improvement over the standard Thomson Parabola when data gathering requires manual scanning. Also notice that the velocity dispersion is constant unlike the standard Thomson Parabola. This feature can greatly simplify data reduction. One disadvantage of this device however is that it requires much larger deflecting fields. Therefore, care must

be taken to insure properly designed electrodes to minimize the possibility of electrical breakdown.

Ion traces calculated for such a modified Thomson Parabola spectrometer are shown in Figure 9. Notice that unlike the standard Thomson Parabola, the spatial resolution improves with ion velocity.

Conventional solid state detectors may not be adequate for implementation inside the spectrometer. This is because the angle of incidence may be too shallow to effectively record the ion tracks. The angle of impact θ, as defined in Fig. 11 is given by

$$\theta = \sin^{-1}(1 + 2 \left(\frac{Z}{A}\right) \left(\frac{e}{m_p}\right) \frac{\nu}{V_o})^{1/2} \tag{36}$$

where ν is the potential difference between the position where the ion first enters the spectrometer and where it strikes the track detector. Figure 10 plots the impact angle as a function of charge-to-mass ratio and the entrance velocity. The ions can be made to strike the track detector surface closer to the detector's normal by the use of a post-acceleration potential located near the detector's surface, but difficulty in controlling electrical breakdown on the track detector surface has been encountered. This problem may be partially resolved with the use of C^2MCP's but the angular dependence of the impacting ions on surface of these devices is gain dependent. Unlike track detectors however, no post acceleration potential is required to achieve velocity threshold requirements.

Conclusions

The conventional Thomson Parabola with the addition of a post-acceleration section appears to best meet the needs for studying velocity distributions of various ion species in laser-produced plasmas possessing velocities of the mid to upper 10^7 cm/s depending on the ion charge state. This spectrometer has the advantages that the deflection fields are small and that the post-acceleration section is physically separate from the deflection region. Also the post-accelerated ions strike the detector surface approximately normally resulting in lower velocity threshold conditions for ion track registration.

For lower velocity ions, the use of C^2MCP's appear attractive for use in the conventional spectrometer. It does offer on-line analysis of the data and does not require a post-acceleration potential.

Significant improvements in data acquisition and analysis in the modified Thomson Parabola over the standard Thomson Parabola can be achieved if the technical difficulties associated with electrical breakdown and ion registration can be solved. These advantages specifically result from the fact that the ion traces are linear which simplify the analysis immensely, both in terms of ion identification as well as from the fact that the velocity dispersion is constant over velocity space.

Acknowledgment

We thank B. Ripin for the useful discussions concerning this ongoing research. This work was supported by the Defense Nuclear Agency.

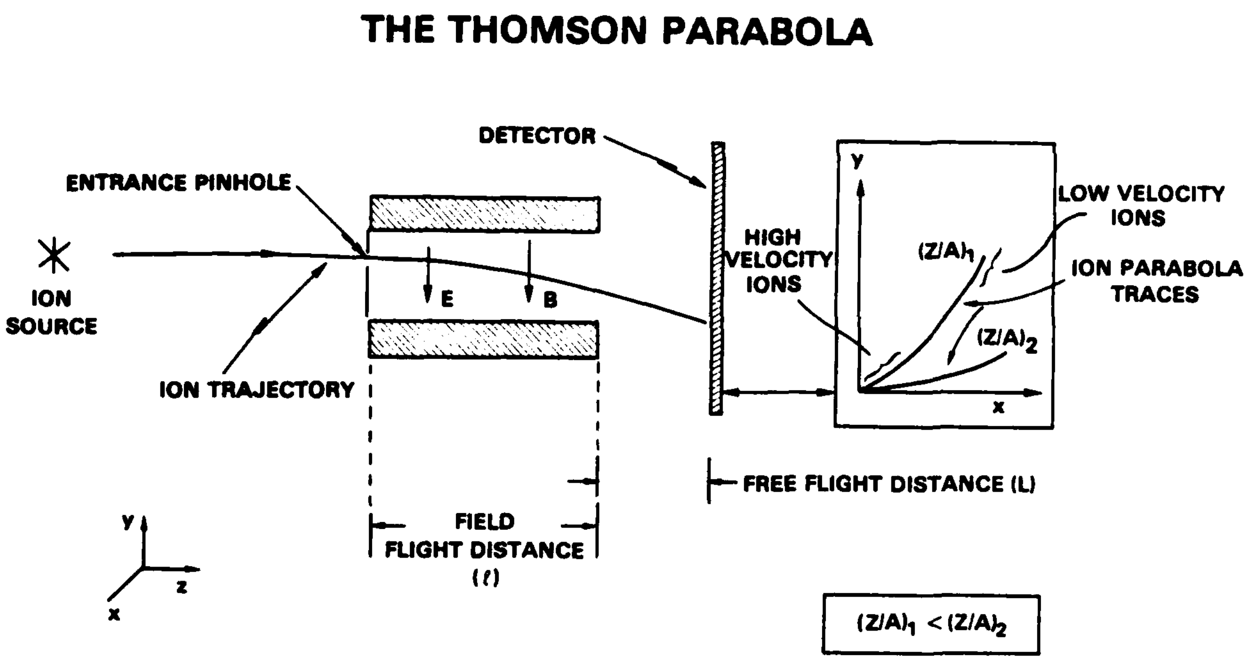

Figure 1

A depiction of a conventional Thomson Parabola ion spectrometer utilizing parallel electric and magnetic deflection fields to separate ions of differing charge-to-mass ratios. After deflection, the ions are spatially recorded on a recording medium such as a track detector. These ions produce a family of parabolic traces of which each member is a unique signature of the ion's charge-to-mass ratio. Ions of differing velocities fall on different locations on the parabolic traces.

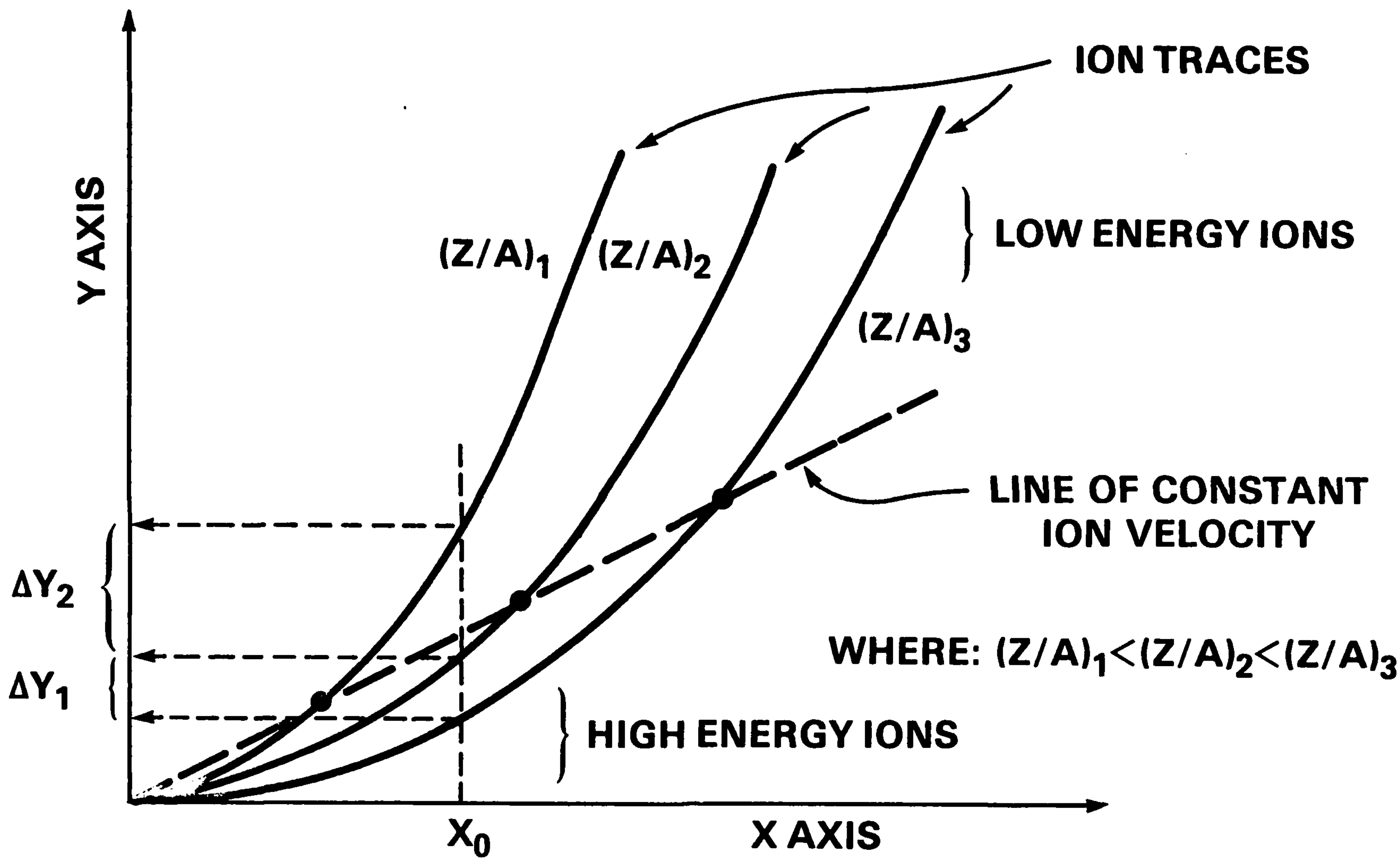

Figure 2

The positioning of parabolic traces for differeing Z/A states as seen by the recording medium. Also radial lines emanating from the origin are lines of constant velocity.

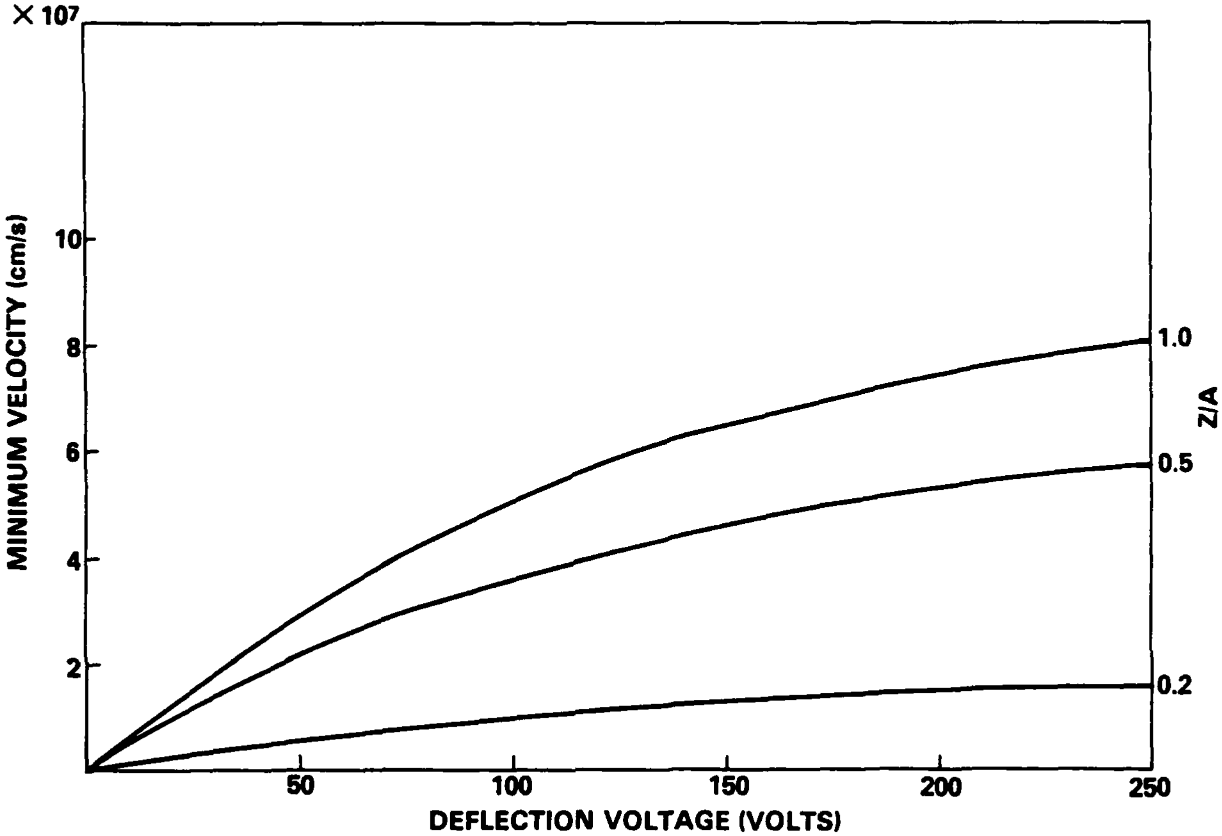

Figure 3

Minimum ion velocity required to traverse the Thomson Parabola spectrometer as a function of deflection voltage. The parameter ℓ and H were taken to be 2.54 cm and 4 mm respectively.

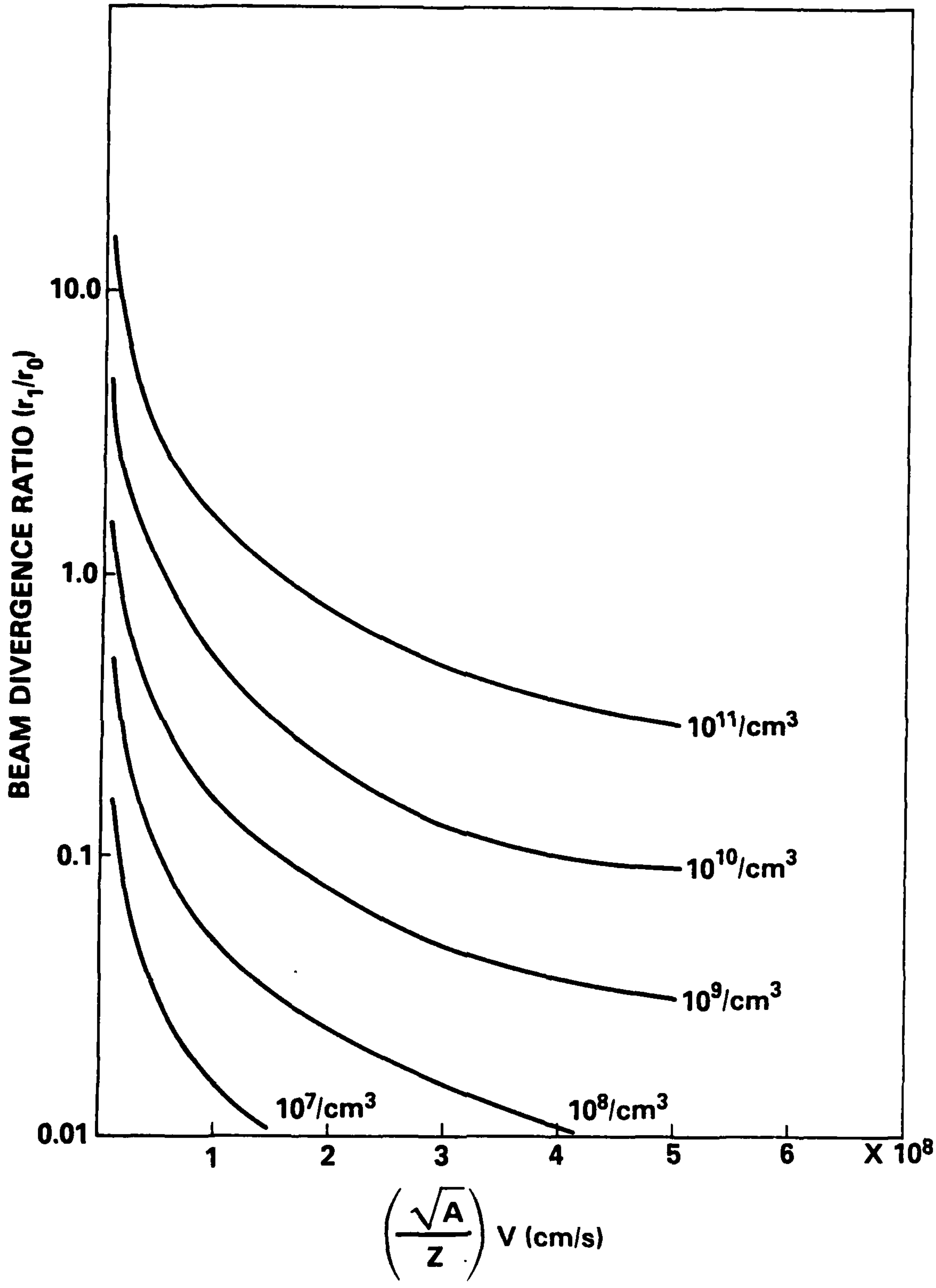

Figure 4

Ion beam divergence ratio as a function of $(\frac{\sqrt{A}}{Z})V$.

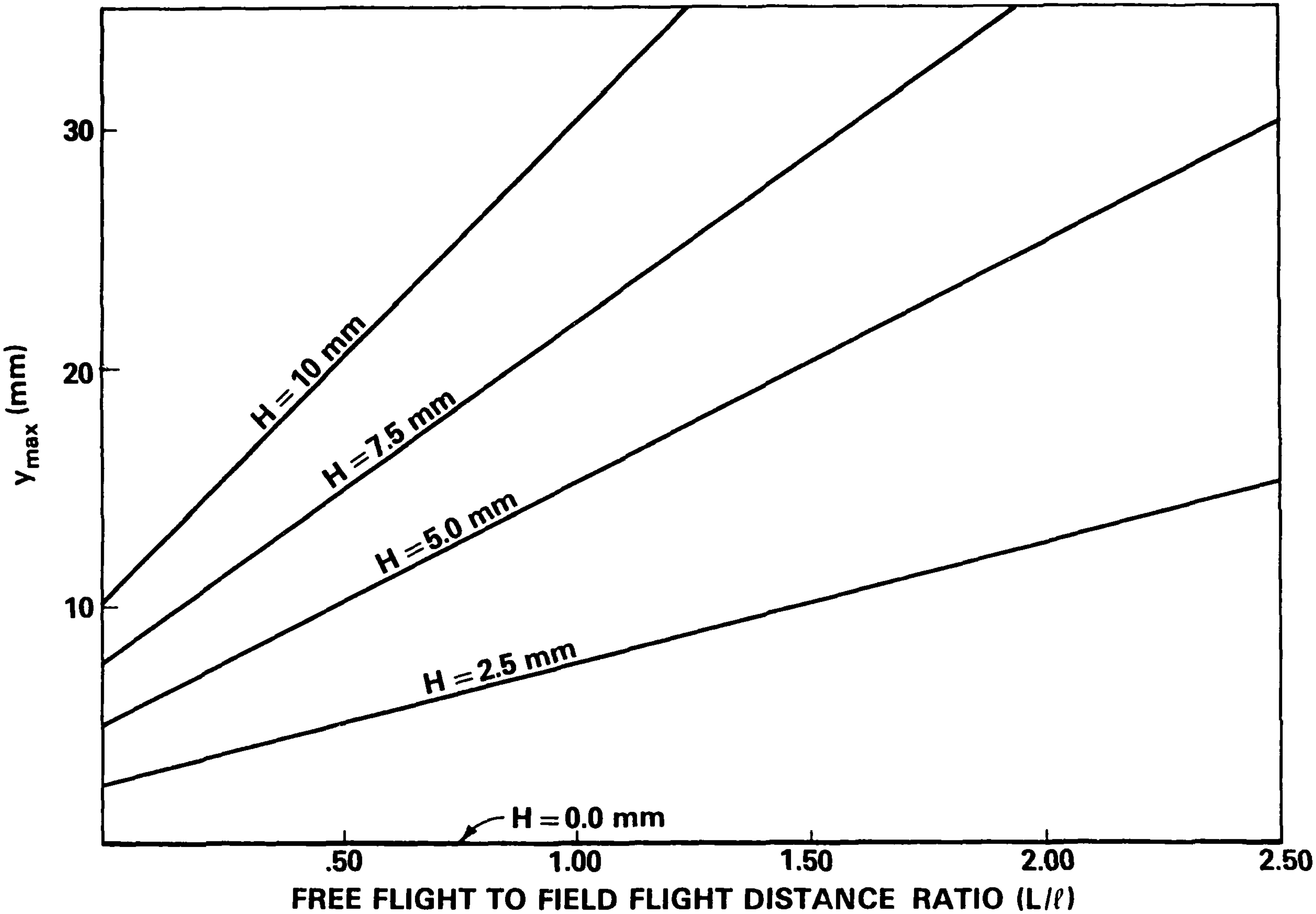

Figure 5

The maximum ion y-displacement as a function of $\frac{L}{\ell}$ for various gap values.

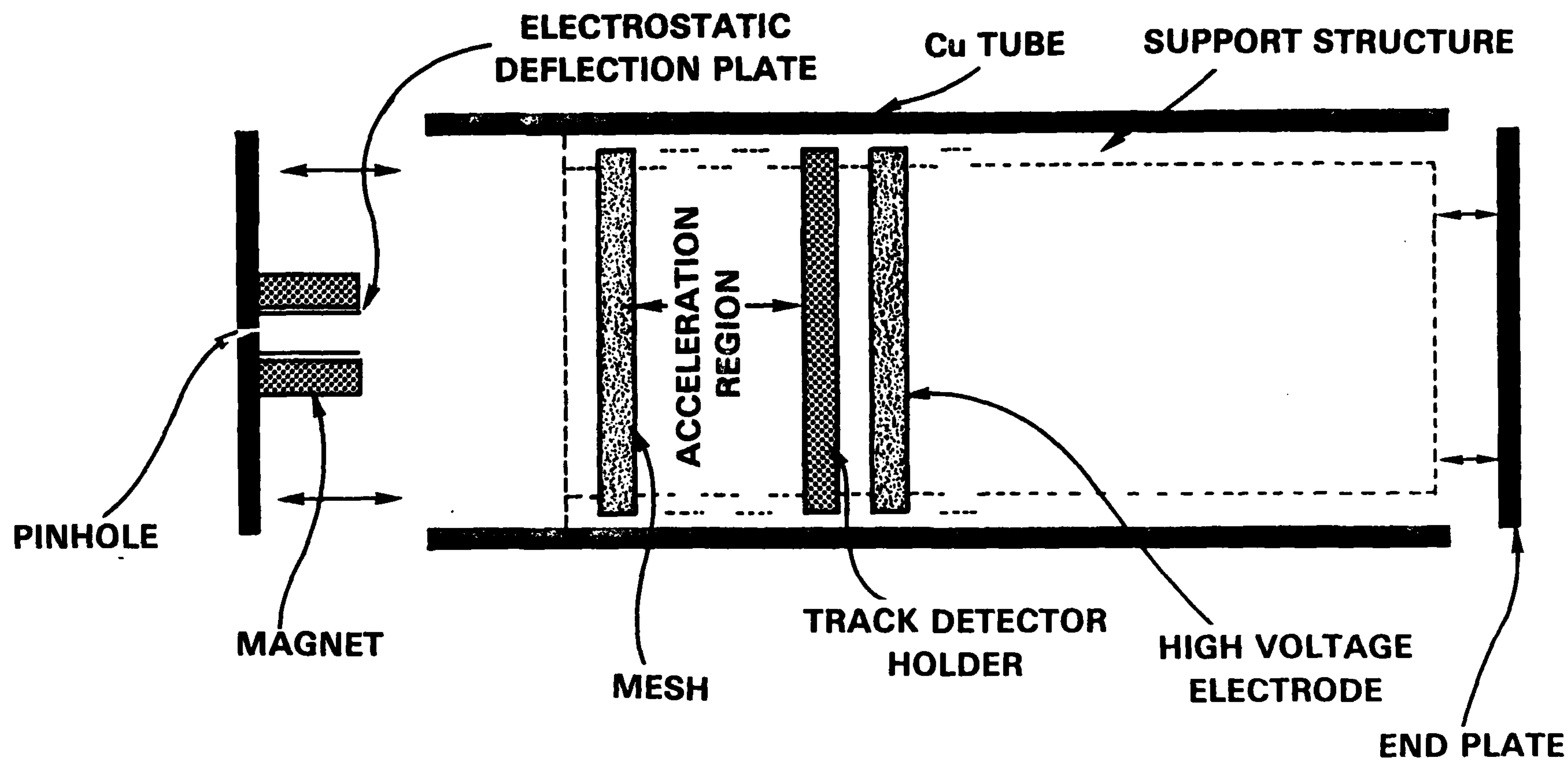

Figure 6

A depiction of a conventional Thomson Parabola spectrometer with a post-acceleration stage to enhance trace registration on the recording medium.

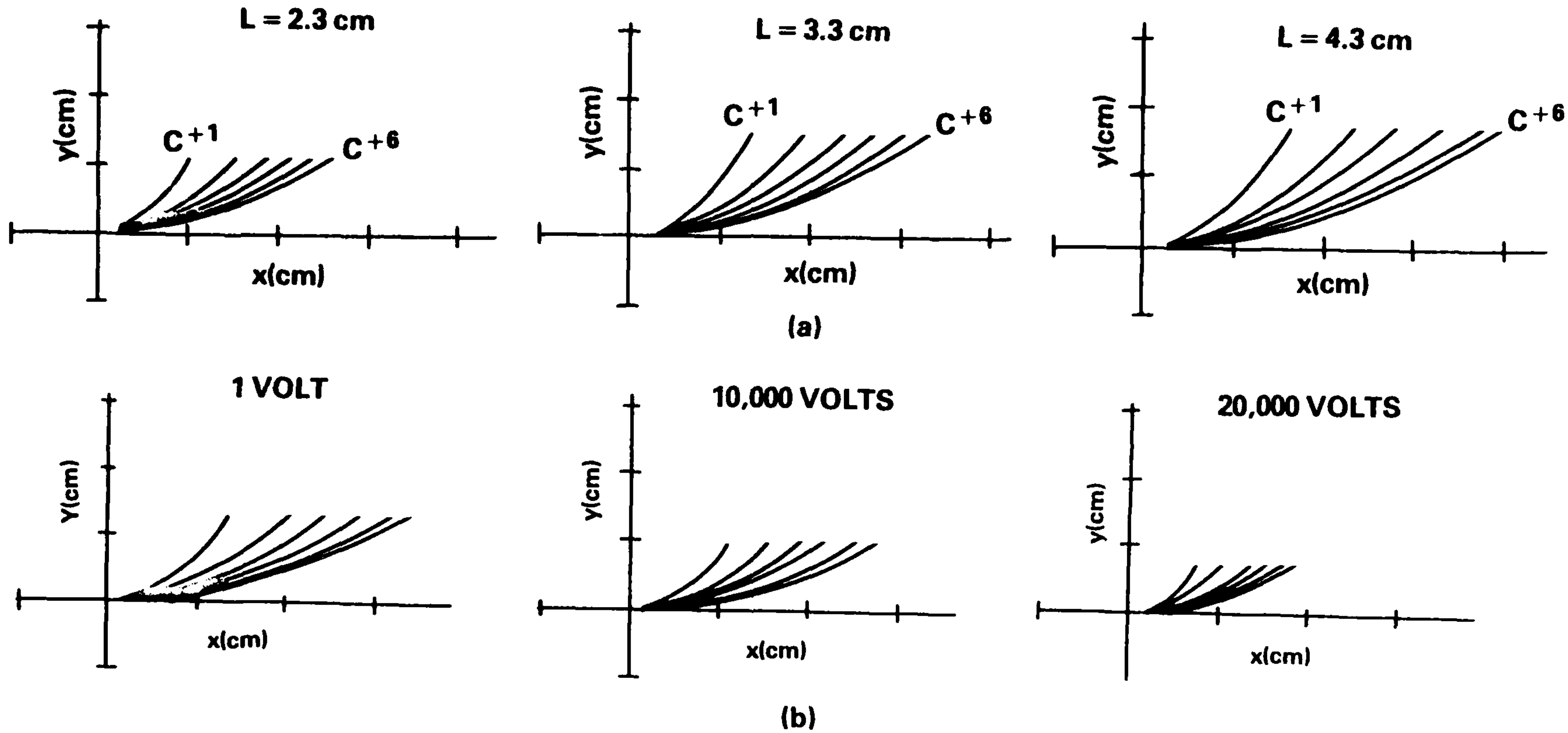

Figure 7

Figure (a) shows the family of ion traces as a function of free flight distance. No acceleration field is applied. Figure (b) shows the alteration in the parabolas for various acceleration voltages. The free-flight-distance is taken to be 2.3 cm in this example.

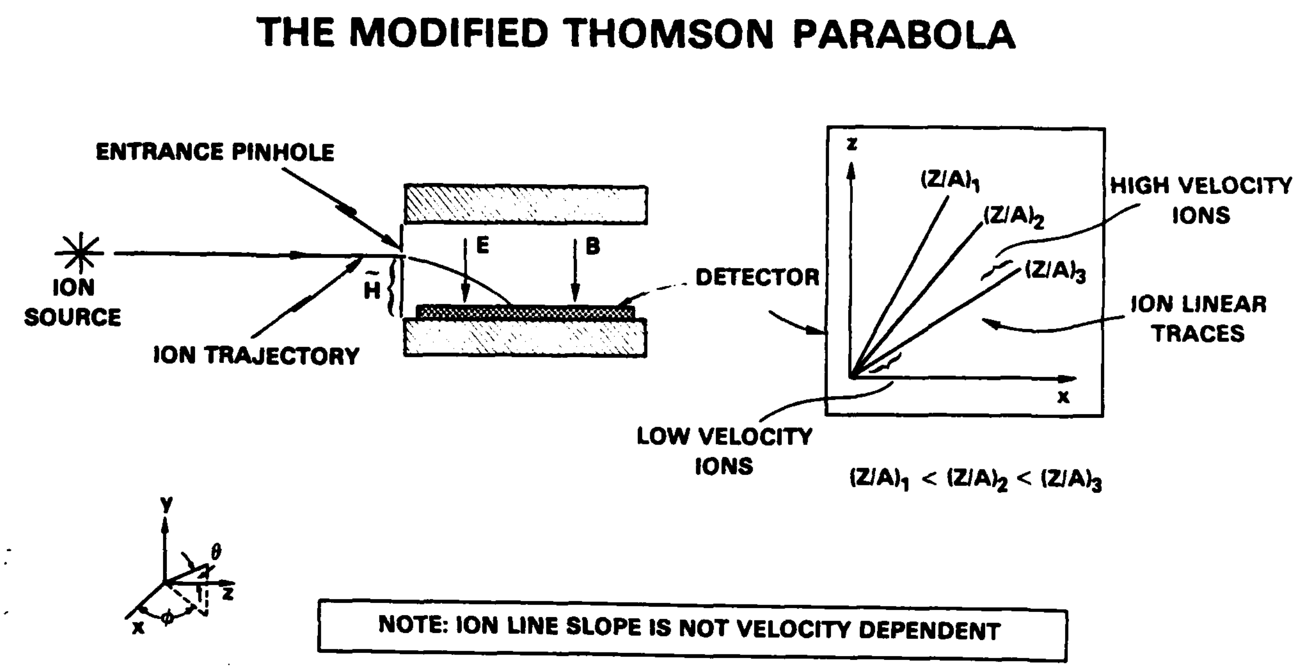

Figure 8

A depiction of a Modified Thomson Parabola ion spectrometer. Ions are deflected by an electric and magnetic field onto a recording medium located on one of the poles of a magnetic piece. A family of straight line traces are produced on the recording medium by the ions of differing charge-to-mass ratios.

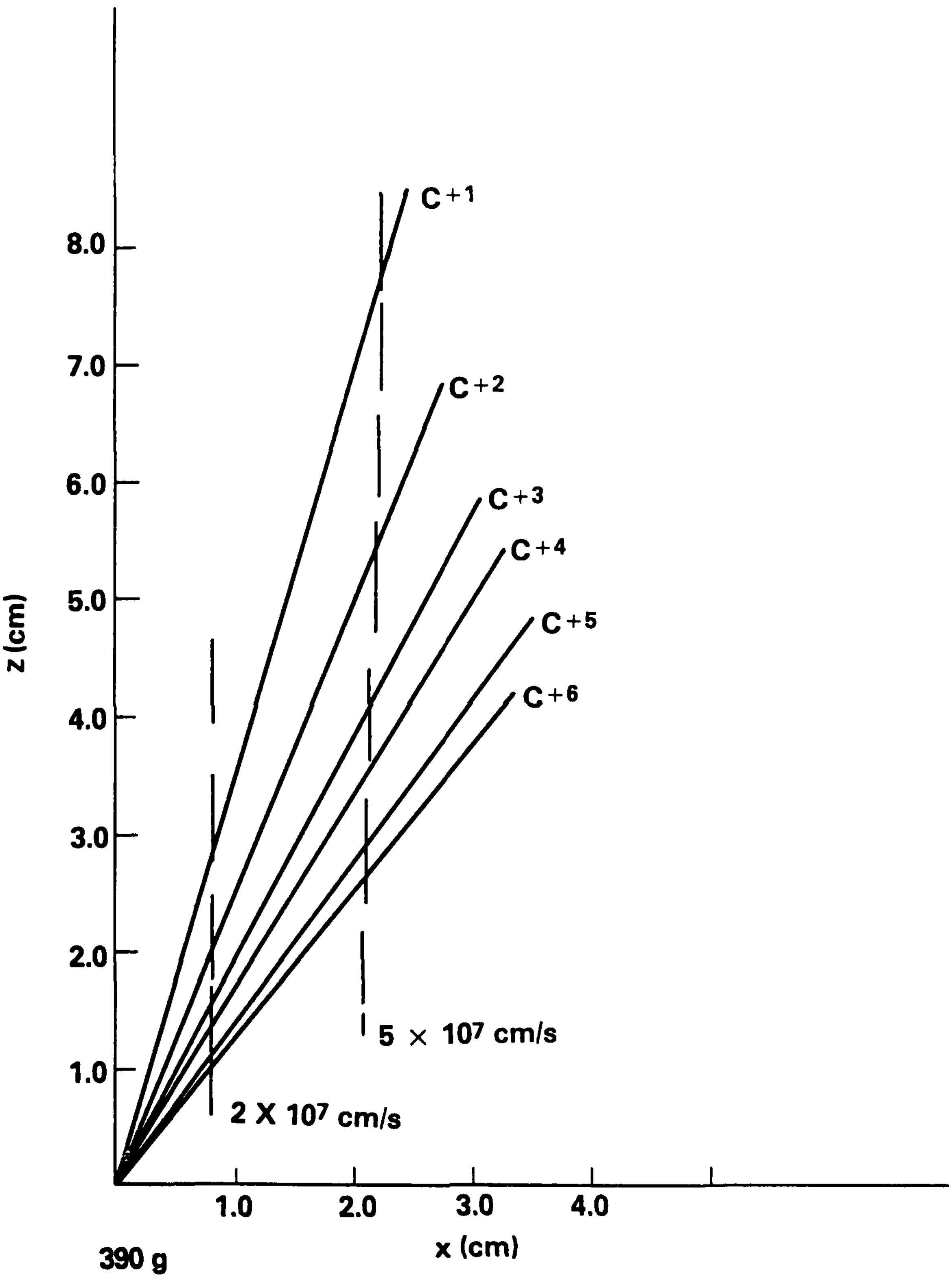

Figure 9

Calculated carbon ion traces produced in a Modified Thomson Parabola.

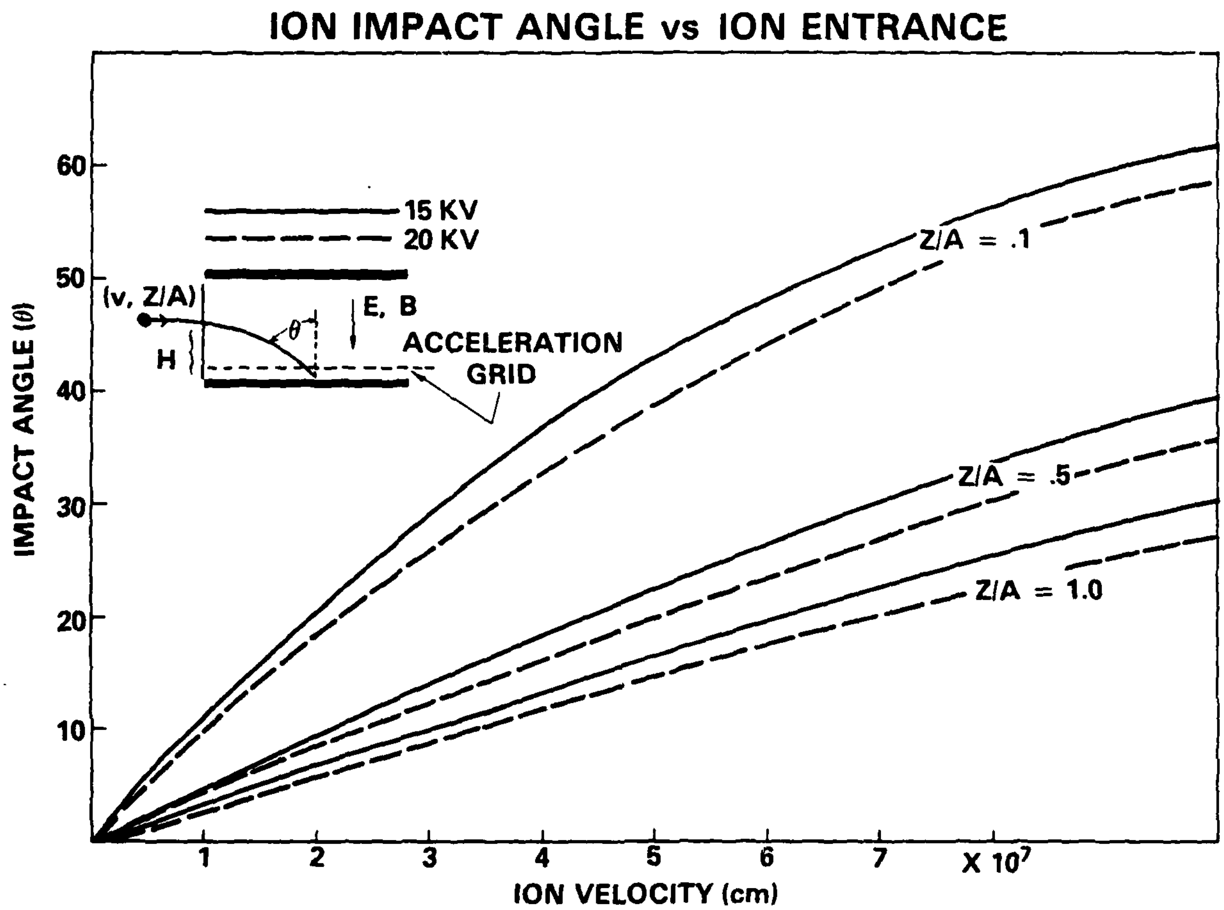

Figure 10
A plot of the ion impact angle as a function of ion velocities for two acceleration potentials and various charge-to-mass states.

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  01CY ATTN C. HUMPHREY

END

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